

## REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	8/15/95	Annual Summary 6/1/94-5/31/95
4. TITLE AND SUBTITLE		5. FUNDING NUMBERS
High Frequency Thermoacoustic Refrigerator		PE 61153 N N 000 1493 J1126 TA 3126
6. AUTHOR(S)		
Orest G. Symko		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)		8. PERFORMING ORGANIZATION REPORT NUMBER
University of Utah Salt Lake City, UT 84112		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSORING / MONITORING AGENCY REPORT NUMBER
Office of Naval Research ONR 331 800 North Quincy Street Arlington VA 22217-5660		
11. SUPPLEMENTARY NOTES		
		
12a. DISTRIBUTION / AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE
Approved for public release Distribution unlimited		

## 13. ABSTRACT (Maximum 200 words)

Results are presented on the development of a high frequency thermoacoustic refrigerator and its performance. The device consists of a piezoelectric driver, operated around 5kHz, which is coupled to a cylindrical resonator containing air at 1 atmosphere as the compressible fluid. For sound levels of 155dB at the stack, a maximum T of 41 C was reached across a cotton wool stack 4mm long. A cooling power of 1.2 watt was achieved with a coefficient of performance of 3. This simple and lightweight refrigerator shows promise for cooling of small samples and electronic components. The performance of this type of refrigerator at high frequencies leads to high efficiency and power density. Research is aimed at improving its performance by optimizing some of the critical parameters such as the sound level and the thermal interface between stack and heat exchangers.

DTIC QUALITY INSPECTED 5

14. SUBJECT TERMS		15. NUMBER OF PAGES		
Thermoacoustic, refrigerator, heat pump.		10		
17. SECURITY CLASSIFICATION OF REPORT		18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified		Unclassified	Unclassified	

Annual Summary Report  
(for year ending May 30, 1995)

"High-Frequency Thermoacoustic Refrigerator"

Orest G. Symko  
Department of Physics  
University of Utah  
Salt Lake City, Utah 84112  
(801) 581-6132

Accesion For	
NTIS	CRA&I <input checked="" type="checkbox"/>
DTIC	TAB <input type="checkbox"/>
Unannounced <input type="checkbox"/>	
Justification _____	
By _____	
Distribution / _____	
Availability Codes	
Dist	Avail and / or Special
A-1	

### Abstract

Results are presented on the development of a high frequency thermoacoustic refrigerator. The device consists of a piezoelectric driver, operated at around 5kHz, which is coupled to a cylindrical resonator containing air as the compressible fluid. For sound levels of 155 dB at the stack, a maximum  $\Delta T$  of 41°C was reached across a stack 4mm long. A cooling power of 1.2 watt was achieved with a coefficient of performance of 3. This refrigerator shows promise for the cooling of small samples and electronic components. Its performance can be improved by optimizing some of the parameters such as the sound levels and the thermal interface between stack and heat exchangers. High frequency operation of this type of refrigerator leads to higher efficiency and improved power density.

## 1. DESCRIPTION OF PROJECT

This project has 3 main goals:

- (i) to develop a simple, compact thermoacoustic refrigerator operating at an audio frequency of ~5kHz.
- (ii) to investigate the performance of a thermoacoustic refrigerator driven at high frequency.
- (iii) to explore new design concepts and materials for thermoacoustic refrigerators.

The study presented here deals with the development and characterization of a high frequency thermoacoustic refrigerator, especially from the point of view of efficiency, power density, and applications. The operation of this type of refrigerator at high frequencies leads to its miniaturization, as it scales directly with the wavelength of the audio driver because of its resonant nature. For special conditions and geometries, thermal phenomena can be quite rapid and this is applied to the cooling device presented here. The high frequency approach brings in new techniques of miniaturization useful for interfacing this type of refrigerator to cooling electronic components and small samples.

## 2. APPROACHES

The thermoacoustic [1] refrigerator has evolved from the class of refrigerators which operate on the surface heat pumping effect [2]; driven on resonance this type of refrigerator achieves an enhancement of thermodynamic effects over dissipative ones. Indeed, its operation at audio frequencies (about 500 Hz) has led to improved power density and to the development of a refrigerator which recently has attracted a great deal of attention [3]. The present project takes such approach even further by developing a refrigerator which is driven at frequencies 10 times higher than the original thermoacoustic refrigerator (which was at 500 Hz). The expected benefits of such an approach are: improved efficiency, higher power density, and miniaturization.

The approach taken here uses components specifically developed for this refrigerator, keeping in mind that the dimensions have to be scaled down by a factor of ten from the conventional thermoacoustic refrigerator. The components are:

- (i) driver: piezoelectric bimorph, operating at 4-5 kHz, coupled to acoustic resonator of refrigerator by a horn, very compact, high power density, very efficient; this unit is shown in Fig. 1.

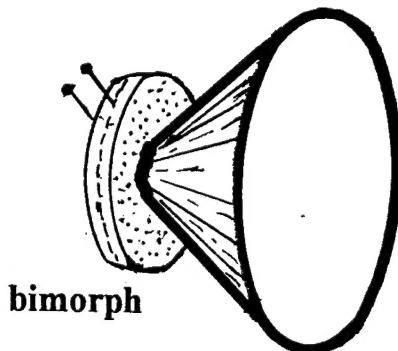


Fig. 1 Piezoelectric driver

- (ii) acoustic resonator: 1 wave cylindrical tube, operated with second harmonic standing wave.
- (iii) primary thermodynamic medium: air at one atmosphere, simple, useful to study basic principles of refrigeration.

- (iv) stack: cotton wool, random configuration.
- (v) heat exchangers: copper plates with perforations, fabricated photolithographically.

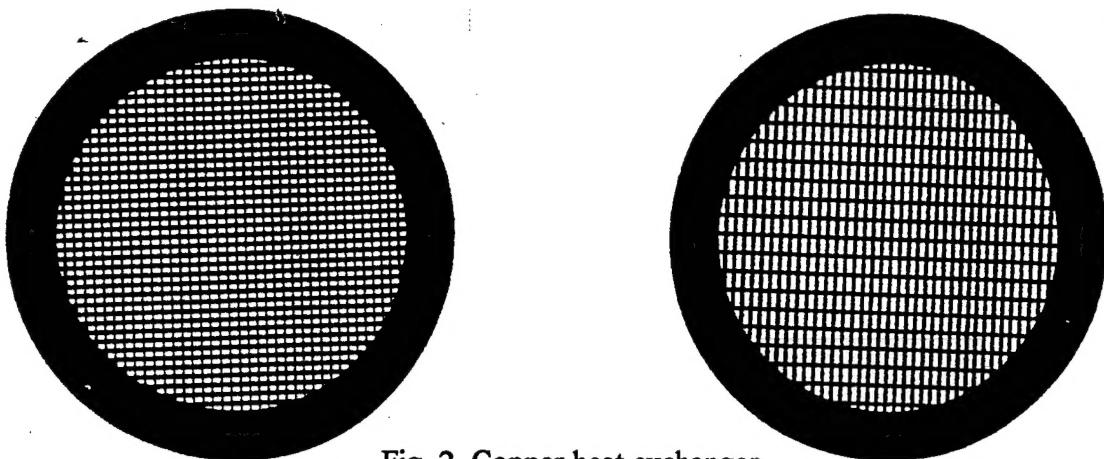


Fig. 2 Copper heat exchanger

The logic for the approach taken here is:

- the efficiency of a piezoelectric driver can be very high, 75-92%, depending [4] on the loading conditions. An important parameter of this device is the electromechanical coupling coefficient ( $k$ ) which is the ratio of (mechanical energy stored/electrical energy applied) $^{1/2}$ . For lead zirconate titanate, EC-66,  $k$  is 0.72.
- power losses in a piezoelectric driver are very small, as its impedance is high (typically 25 to 500 ohms); it is a voltage device rather than a current device [5]. The small amount of heat generation is caused by hysteresis due to domain reversals in the dielectric.
- operation at 5 kHz provides a better acoustic impedance match of the thermodynamic medium to driver, i.e. the impedance of air matches the driver better at 5 kHz than at 500 Hz since this depends on  $\omega m$ ,  $\omega$  being the operating frequency and  $m$  the mass of driven air [4].
- power density is large in the driver and refrigerator (it varies as  $\omega$ ).
- critical gradient increases with frequency  $\omega$  since  $VT_{crit} = \frac{2\pi(\gamma-1)}{\lambda} \tan\left(\frac{2\pi x}{\lambda}\right)$ .
- since the volume of the refrigerator goes as  $1/\omega$ , a small volume will favor quick cool down and hence short time constants.

### 3. ACCOMPLISHMENTS

#### A. Apparatus

One version of the refrigerator is shown in simplified form in Fig. 3. It is 10 cm long and this includes the cylindrical acoustic resonator driven at its second harmonic (5 kHz). It is driven at one end by a piezoelectric bimorph driver (Motorola) whose diameter is 23 mm; it is loaded by a paper exponential horn whose mouth has a diameter of 41 mm. The total mass of this driver is 1.34 g. Its sensitivity is  $\sim 94$  dB/1W/1m.

The stack consists of a random uniform packing of cotton wool, pressed between the cold and the hot heat copper exchangers. Its optimum length  $\Delta x$  was determined experimentally to be 4 mm. The hot heat exchanger is anchored thermally to another heat exchanger which is more massive and which has a larger thermal conductance.

For our case the critical temperature gradient is  $120^\circ\text{C}/\text{cm}$  and this determines the maximum  $\Delta T$  which can be achieved across the stack. (i.e.  $50\text{--}60^\circ\text{C}$ ).

For simplicity we chose the working fluid to be air at one atmosphere. In that case the wavelength at  $5\text{kHz}$  is  $\sim 6.9\text{ cm}$ , and this dictates the dimensions of the refrigerator.

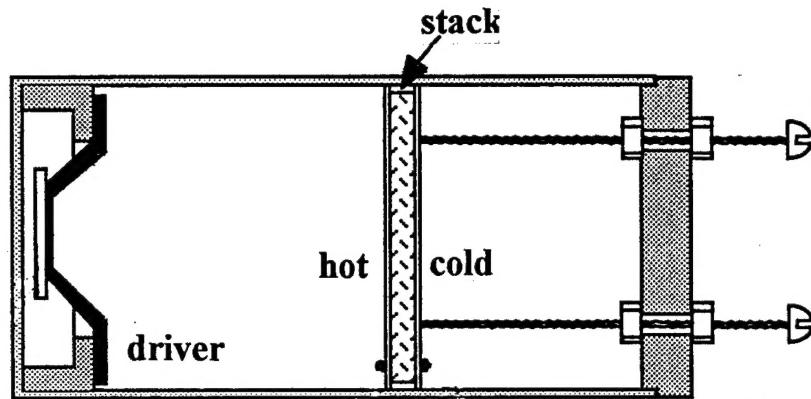


Fig. 3 Basic high frequency refrigerator

#### B. Results

(i) Fig. 4 shows a typical performance for our refrigerator producing a  $\Delta T=38^\circ\text{C}$  for a sound level of  $155\text{dB}$  at the stack; this corresponds to a normalized sound pressure level (to working gas pressure) of  $P_1/P_m = 1.1\%$ . The response is rapid being in the range of seconds.

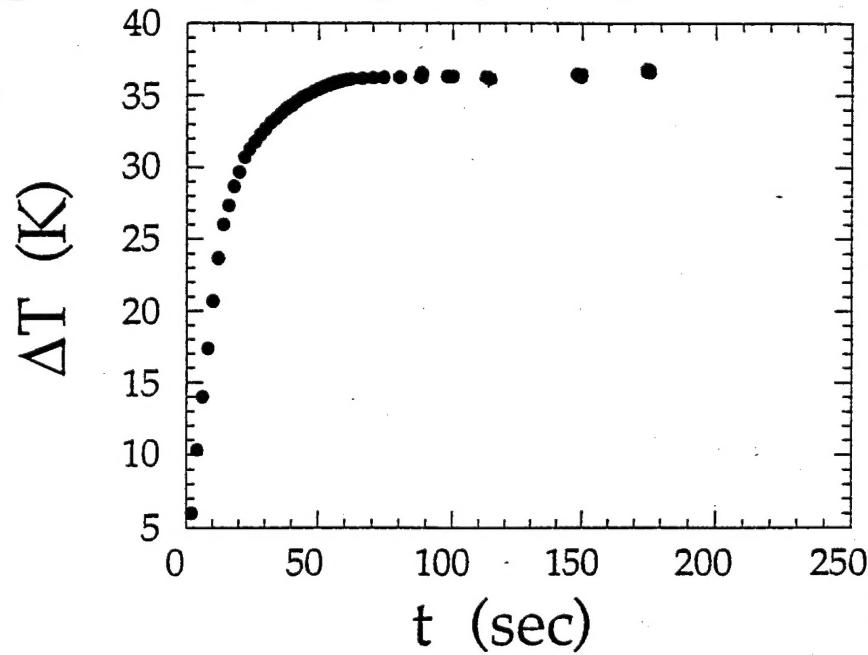


Fig. 4  $\Delta T$  as a function of time

The cooling power is calculated to be 1.2 watt and this gives a coefficient of performance C.O.P. of 3. The C.O.P. is defined as: (cooling power/sound power in) at stack; this is not the conventional definition of C.O.P. as in a home refrigerator! The normalized temperature gradient  $\Gamma (= \Delta T / \Delta T_{\text{crit}})$  for this case is 0.58.

With similar conditions the largest  $\Delta T$  that was achieved was  $41^\circ\text{C}$ . This is a reasonable  $\Delta T$  as the  $\Delta T_{\text{crit}}$  across the 4mm long stack is  $62\text{K}$ . Higher  $\Delta T$ s were not achieved because we worked

at the power limit of the Motorola driver; prolonged operation caused failure of the driver. This limitation can be overcome by using a more powerful driver (for example, a unimorph).

(ii) The incorporation of this device into a useful refrigerator requires thermal isolation and adequate thermal anchoring of the hot heat exchanger to room temperature and cooling of the resonator by the cold heat exchanger. Thermal isolation was provided by a vacuum jacket around the cold part. Fig. 5 shows the basic arrangement of this apparatus. The resonator is reduced to a smaller diameter in order to amplify the sound level [6]. In this case, cooling was also observed and

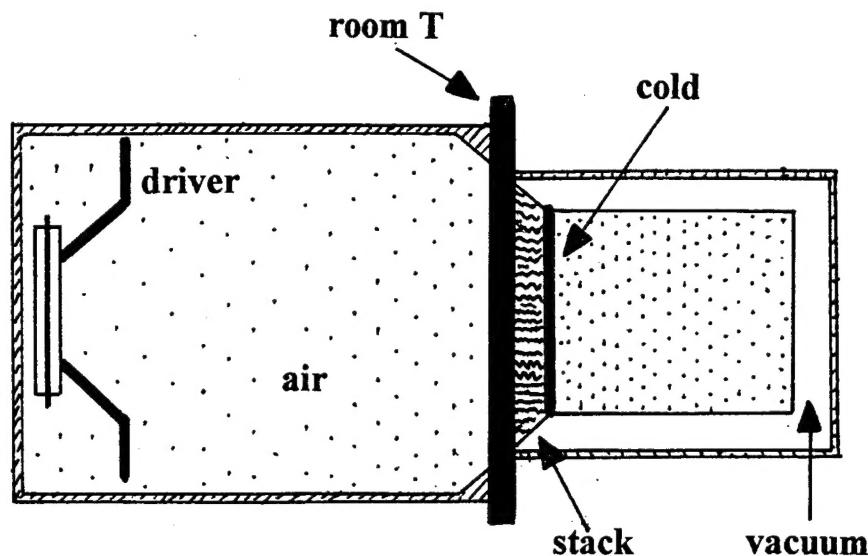


Fig. 5 Thermoacoustic Refrigerator with thermal isolation

the cold heat exchanger cooled the acoustic resonator (20 c.c. volume) with a time constant of a few minutes. Both the hot end and cold end of stack showed a saturation with time of their respective temperatures, maintaining a fairly constant  $\Delta T$  between them. However the temperature of the hot end of the stack was 30 to 40% above that of the hot heat exchanger anchored to room T. This indicates that there is a problem in heat transfer between stack and heat exchanger. Indeed such a problem was anticipated as the thermal resistance between 2 solids touching each other lightly is approximately  $1-10^\circ\text{C cm}^2/\text{W}$ . Fig. 6 shows how the hot end of stack rides above room temperature even though the hot heat exchanger was well anchored thermally to room temperature.

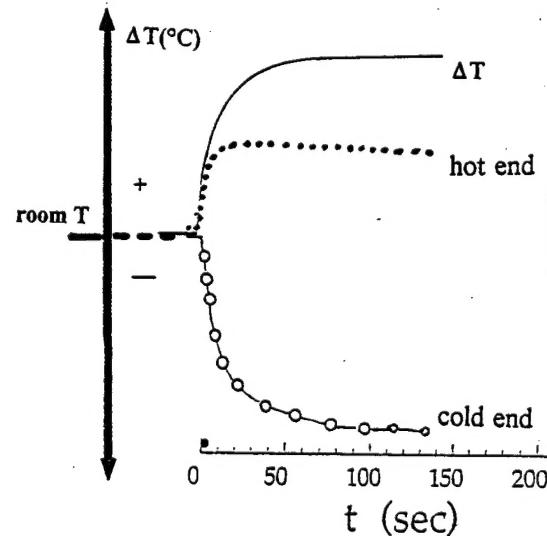


Fig. 6 Temperature of cold side of stack and of hot side

### C. Discussion

The performance of the high frequency thermoacoustic refrigerator shows that a simple miniature refrigerator can be developed for cooling all sorts of small objects, ranging from biological samples to electronic components. The maximum  $\Delta T$  of  $41^{\circ}\text{C}$  achieved here at sound levels of 155dB compares favorably to the performance of regular thermoacoustic refrigerators. Better performance is anticipated since the present high frequency refrigerator is not optimized. The problems that have to be solved are:

- (i) Heat transfer at stack-exchanger interface. The gas displacement in the sound field is too small (less than 0.1mm) to be useful in transferring heat from stack to heat exchanger. We are relying on the mechanical contact between stack and heat exchanger for heat transfer across the large boundary resistance which exists at the interface. Usually it is difficult to transfer heat across a surface above  $1 \text{ watt/cm}^2$ . Our geometry has to be changed in order to improve the heat transfer.
- (ii) Gas mixtures for thermodynamic compressible medium. The Prandtl number for air is 0.71; some gas mixtures have much smaller Prandtl numbers and hence we will try them. This approach has been successful in the regular thermoacoustic refrigerator [7].
- (iii) Achieving higher sound power levels. We have reached the limit with the Motorola driver at a sound level of 155dB (there is a variation of  $\sim \pm 5\text{dB}$  from one driver to the next in a batch!). Higher levels are expected from a unimorph (which can handle higher power levels) or from an array of piezoelectric elements. Recently, polymer piezoelectric materials have shown much promise as high power drivers.
- (iv) Larger  $\Delta T$ . Although we are limited by the length  $\Delta x$  of the stack, larger  $\Delta T$ s can be achieved by using dual stack-heat exchanger units (this was demonstrated in the previous report, of last year) at appropriate locations in a second or higher harmonic or by using gases with higher speed of sound.

In conclusion, by operating the thermoacoustic refrigerator at high frequencies, we have scaled down [8,9] its size and weight and increased its efficiency. The small volume of this refrigerator leads to a large power density which can be used for all sorts of refrigeration applications.

## References

- [1] J.C. Wheatley, T. Hofler, G.W. Swift, and A. Migliori, Phys. Rev. Lett. 50, 499 (1983).  
G.W. Swift, J. Acoust. Soc. Am. 84, 1145 (1988).
- [2] W.E. Gifford and R.C. Longsworth, Adv. Cryog. Eng. 11, 171 (1966).
- [3] S.L. Garrett and T.J. Hofler, Technology 2001, NASA Conf. Publ. 3136, Vol. 2, 297 (1991).
- [4] T. Tanaka in *Piezoelectricity*, ed. Rosen, Hremath, and Newnham, 289 (1992).
- [5] C.P. Germano, IEEE Trans. on Audio and Electro-acoustics AU-19, 6 (1971). J. Kirtz, IRE Trans. on Ultrasonic Eng. UE, 14 (1961).
- [6] H. Oberst (and Beranek), J. Acoust. Soc. Am. 12, 308 (1940).
- [7] J.A. Adoff, M.S. Thesis, Naval Postgraduate School, Rept. AD A241 320, Monterey, CA (1990).
- [8] J.R. Olson and G.W. Swift, J. Acoust. Soc. Am. 95, 1405 (1994).
- [9] A.J. Organ, *Thermodynamics and Gas Dynamics of the Stirling Cycle Machine*, Cambridge University Press, 1992, p. 62.

#### 4. PUBLICATIONS

"High Frequency Thermoacoustic Refrigerator Operated with Air", by O.G. Symko, T. Klein, and D.J. Zheng, in preparation.

We intend to publish this when we reach a  $\Delta T$  of 50°C.

#### 5. PERSONNEL

- Thierry Klein, Postdoctoral Fellow
- De Juan Zheng, Research Associate Professor
- Orest G. Symko, Professor and Principle Investigator

OFFICE OF NAVAL RESEARCH  
PUBLICATION/PATENTS/PRESENTATION/HONORS REPORT  
for  
1 Oct 94 through 30 May 95

R&T Number: 3126

Contract/Grant Number: N 000 1493 J 1126

Contract/Grant Title: High Frequency Thermoacoustic Refrigerator

Principal Investigator: Orest G. Symko

Mailing Address: Department of Physics  
University of Utah  
Salt Lake City UR 84112

Phone Number (with Area Code): (801) 581-6132

E-Mail Address: orest@mail.physics.utah.edu

- a. Number of Papers Submitted to Referred Journal but not yet published: 0
- b. Number of Papers Published in Referred Journals: 0  
(list attached)
- c. Number of Books or Chapters Submitted but not yet Published: 0
- d. Number of Books or Chapters Published: 0  
(list attached)
- e. Number of Printed Technical Report & Non-Referred Papers: 0  
(list attached)
- f. Number of Patents Filed: 0
- g. Number of Patents Granted: 0  
(list attached)
- h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 0
- i. Number of Presentation at Workshop or Prof. Society Meetings: 1
- j. Honors/Awards/Prizes for Contract/Grant Employees: 1  
(list attached, this might Include Scientific Soc. Awards/Offices,  
Promotions, Faculty Award/Offices etc.)
- k. Total number of Graduate Students and Post-Docs Supported at least 25%, this  
year on this contract/grant:

Grad Students 0 and Post Docs 2

How many of each are females or minorities? (These 6 numbers are for ONR's EEO/Minority Reports; minorities Include Blacks, Aleuts Amindians, etc and those of Hispanic or Asian extraction/nationality. This Asians are singled out to facilitate meeting the varying report semantics re "under- represented")	<input type="checkbox"/> Grad Student Female _____
	<input type="checkbox"/> Grad Student Minority _____
	<input type="checkbox"/> Grad Student Asian e/n _____
	<input type="checkbox"/> Post-Doc Female 1
	<input type="checkbox"/> Post-Doc Minority _____
	<input type="checkbox"/> Post-Doc Asian e/n _____